

A hypothesis on the selective advantage for sleep

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In this note, we present a hypothesis for the emergence of the phenomenon of sleep in organisms with sufficiently developed central nervous systems. We argue that sleep emerges because individual neurons must periodically enter a resting state and perform various “garbage collection” activities. Because the proper functioning of the central nervous system is dependent on the interconnections amongst a large collection of individual neurons, it becomes optimal, from the standpoint of the organism, for these garbage collection activities to occur simultaneously. We present analogies with complex structures in modern economies to make our case, although we emphasize that our hypothesis is purely speculative at this time. Although the “garbage collection” hypothesis has been previously advanced, we believe that our speculation is useful because it illustrates the power of a general paradigm for understanding the emergence of collective behavior in agent-built systems.

Keywords: Sleep, collective behavior, swarming, synchronization

Sleep is one of the most intriguing phenomena exhibited by multicellular organisms. It occurs in almost all organisms with a central nervous system, and is characterized by a period during which there is a marked decrease in the arousal level of the organism.

The difficulty in understanding the necessity of sleep derives from the observation that sleep-deprived organisms do not show signs of physical damage, and yet they are characterized by impaired cognitive abilities. In extreme cases, sleep deprivation can even lead to death.

A hypothesis for sleep, advanced by Francis Crick, is that sleep is a way for the brain to perform various upkeep, or alternatively, “garbage collecting” functions necessary for proper brain function [1]. More specifically, sleep is a time when the brain sorts through various stored memories, and discards those deemed unessential, while processing those deemed essential for long-term storage.

There is now evidence suggesting that Crick’s hypothesis may be correct: It has been discovered that neurons contain a protein, termed Fos, which is involved in proper neuronal function [1]. During periods of neuronal stimulation, Fos naturally builds up, apparently as a by-product of various neuronal activities. Proper neuronal function is no longer possible once Fos levels reach a critical level. During the sleep state of an organism, Fos levels rapidly drop. Apparently, the Fos protein acts as a molecular switch that regulates various genes involved in proper neuronal function [1]. During sleep, these genes are suppressed, allowing the neuron to re-set for the next period of wakefulness.

We should note a parallel between this behavior and the build-up of lactic acid during intense muscular activity. The accumulation of lactic acid causes the muscles to tire, and to cease functioning, before permanent damage occurs. Similarly, it is apparent that Fos itself may not be necessary for the survival of the neuron, but rather

acts as a chemical signal that regulates external input to the neuron in such a way to prevent neuronal damage.

While there is emerging evidence that individual neurons may periodically require periods of limited external stimulation in order to “reset” themselves, this in and of itself does not explain sleep as collective synchronization phenomenon, whereby the neurons of the central nervous systems engage in their respective upkeep tasks simultaneously.

Here, we argue that the drive for such “swarming” behavior is that it is optimal, from the standpoint of brain function and therefore organismal survival, for neurons to engage in their respective “garbage collection” activities together. This optimal garbage collection strategy is derived from the highly connected, interdependent nature of neurons in a central nervous system. Therefore, if some neurons were to engage in garbage collection independently of others, this would impede the proper functioning of other neurons, who may rely on the “sleeping” neurons for important information.

To understand this argument in terms of a more general paradigm, we note a recent speculative paper by the author regarding the nature of RNA biochemical networks in eukaryotic cells [2]. In this work, the author argued that the RNA biochemical networks in eukaryotic cells may in many ways be viewed as an RNA-“community”, in the sense that agent-based models will likely be as useful in understanding the structure of such biochemical networks as the traditional pathway-based approach of Systems Biology. Because the emergence of other complex structures, such as the brain and highly networked societies, is driven by the self-organization of agents acting under certain selection pressures, it was then argued that the emergence of complexity may be seen as the outcome of a series of agent-based behavior at various length scales, where the collective interactions of agents at one length scale produce a single agent at the next length scale. Thus, there are likely analogous structures and behaviors amongst the various length scales, so that, by observing such structures at one length scale, it may be possible to infer or understand similar structures

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at another length scale.

To apply this to the problem of sleep, we use two examples, that of a city, and that of a large corporation. First of all, we note that, just as with complex organisms, a city has a periodic cycle of activity, characterized by high levels of activity during the day, followed by periods of relatively low levels of activity at night. The central reason for this collective behavior is that the individual agents constituting a city, namely humans, are awake during the day and sleep at night. Since the brain is a collection of neurons whose interconnections are driven by a biochemical reward-punishment system, it suggests that the brain requires sleep because individual neurons require periods of reduced activity.

An analogy with a large corporation is even more useful for gaining insight. A large corporation is often divided into numerous branches (even a smaller company may have many distinct departments), all of which are required to interact with one another to a certain extent, in order for the corporation to function properly. Focusing on one such subdivision, it is natural to suppose that during the normal operations of the subdivision, various transactions occur which are temporarily recorded using locally available materials (keeping a running receipt of the day's purchases, for example). However, for proper functioning of the subdivision, and of the corporation in general, which requires up-to-date, consolidated information from its various components, it makes sense for each subdivision to periodically sort through its various transactions and update necessary information, such as inventories and finances, for later use. Once this update has been performed, much of the information from the numerous smaller transactions can be discarded.

If the various subdivisions of a corporation are highly interconnected, it will likely be most efficient if the various subdivisions engage in their various "housekeeping" tasks simultaneously. First of all, this guarantees that all the subdivisions of a corporation will be operational at the same time. Secondly, if the various subdivisions of a corporation do not perform their upkeep tasks simultaneously, then one subdivision might make use of information from another subdivision before the information has been properly updated, and the result can be a cascade of temporally out-of-phase information transfer that can cause a system failure. While this may not manifest itself as physical damage to the actual structures of the corporation, it may lead to an inability for the corporation to properly interact with the external environment, causing it to fail.

The applicability of this analogy to the brain should be clear: Because the brain is a highly interconnected computational network of neurons, for the brain to properly process external information it is necessary that the information stored in the various parts of the brain be temporally in-phase. Furthermore, during periods of wakefulness, the brain will function optimally if all neurons are fully engaged in brain activity.

Our analysis is not complete, however, since, due to

modern technology, there are now corporations that can perform their upkeep tasks in real time, without having to shut-down. Essentially, modern technology has reached a point where information transfer within a corporation is faster than the rate of generation of information due to external inputs, so that periodic shut-down and performance of upkeep tasks are not necessary (however, even in this case, there are likely other time scales on which shut-down may be necessary).

To resolve this apparent contradiction for our explanation for sleep, we first point out the possibility that, at least in some organisms that sleep, neuronal biochemistry and brain circuitry will evolve to a point where only minimal sleep will be required for proper organismal function.

Second, while it is in principle possible for individual neurons to continuously switch between various information transfer, processing, and consolidation functions, it is energetically costly to do so, since the neuron would have to maintain the various pathways turned on at all times. Furthermore, the switching strategy itself has an energetic penalty.

Therefore, sleep is also an example of the general idea that when a system is faced with a requirement to continuously perform a given set of tasks, it is often the least energetically costly strategy to complete each of the tasks sequentially, instead of continually switching from one to the other. The optimality of this strategy increases as the base rate at which tasks must be performed approaches the saturation point of the system. That natural selection drove central nervous systems to process information close to their saturation point is not unexpected, since for a given energy input, those organisms that can process more information will likely have a greater survival advantage.

We conclude with an additional hypothesis that the synchronized sleep behavior in neurons is explicitly encoded into neural genomes. By analogy with cancer and other phenomena involving defection from collective behavior, we also hypothesize that there exist sleep disorders where some neurons, either through defective regulatory genes or some other external influence, do not coordinate their sleep behavior with other neurons, and engage in their upkeep tasks independently of the rest of the brain. Just as with tumor cells, there are likely always a few neurons who engage in this behavior. However, if this behavior becomes widespread, with the brain divided into numerous distinct regions, each of which "sleep" on their own, the result could be a sleep disorder that is potentially life-threatening. We also claim that this hypothesized ability of individual neurons to "sleep" independently of the rest of the brain may occur as a neuronal stress response, triggered by overstimulation of the central nervous system.

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- [1] http://www.med.harvard.edu/publications/On_The_Brain/Volume5/Number3/Sleep.html
 - [2] E. Tannenbaum, q-bio.MN/0412027 (2005).